



CARLO GAVAZZI SPACE SpA

RICH SYSTEM

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REGISTRAZIONE DELLE MODIFICHE / *CHANGE RECORD*

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ACRONYM LIST

AD	Applicable Document
BOL	Begin Of Life
CGS	Carlo Gavazzi Space
EOL	End Of Life
GMM	Geometrical Mathematical Model
I/F	Interface
ISS	International Space Station
MLI	Multi Layer Insulation
MPA	Minimum Propulsion Attitude
RD	Reference Document
TBC	To Be Confirmed
TBD	To Be Defined
TBW	To Be Written
TCS	Thermal Control Subsystem
TMM	Thermal Mathematical Model
TOF	Time Of Flight
TRP	Temperature Reference Point
w.r.t.	With respect to

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1. SCOPE

This document describes the thermal mathematical and geometrical models of ToF (Time of Flight), a subdetector included in AMS-02. These models were built to investigate the thermal behavior during all mission phases. Analysis results are presented as well.

2. RELEVANT DOCUMENTS

The following documents are to be considered relevant to the ToF program.

2.1 APPLICABLE DOCUMENTS

AD #	Document Number	Issue	Date	Rev.	Title
1	AMS02-IC-CGS-001	2	June, 2003		AMS-02 Thermal Control System Interface Control Document

2.2 REFERENCE DOCUMENTS

N/A

3. PURPOSE

This report contains the description of the Thermal Mathematical Model (TMM) and the Geometrical Mathematical Model (GMM) developed to study the thermal behavior of Time Of Flight (TOF) detector and to perform the sizing of the following items:

- MLI layers definition;
- Heater patches ;

Steady state and transient thermal analysis have been performed using the SINDA/FLUINT network analyzer, to investigate the thermal behavior of the ToF subdetector installed on AMS-02, during the design orbital cases, considering worst hot and cold conditions, , properly selected by AMS-02 thermal team at system level.

A Thermal Mathematical Model has been generated, consisting of **885** nodes for the representation of the following items:

- Carbon fiber box (393 nodes)
- PMTs (492 nodes)

A Geometric Mathematical Model has been built up in RadCad to calculate radiative heat exchange on the basis of suitable thermo-optical properties.



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4. REQUIREMENTS

4.1 TEMPERATURE REQUIREMENTS

The following temperatures are assumed as design limits for the ToF PMTs

Operating Range: -30°C ÷ +50°C
Non Operating Range: -30°C ÷ +50°C

5. THERMAL CONTROL CONCEPT

Due the low dissipation of the ToF (3 68W for the entire system) , a radiator is not the most effective solution. The percentage of the TOF bulk dissipation is little if compared with the external impinging heat fluxes , both UV and IR.

For this reason the temperature of a potential radiator shall not be driven by the inside coming dissipation but mostly from the external natural and induced environment.

The proposed thermal control concept is based on the detector completely covered by Multi Layer Insulation (MLI). The heat leakage through the layers is of the same order of the TOF bulk dissipation and this is the philosophy followed to reject out the dissipated power.

All the external surface of the carbon fiber box is covered with a 6 layer MLI blanket.

The 6 layers MLI insulation effectiveness performance has been modeled by means of an experimental array (provided by MLI supplier and shown in Fig. 5-1) giving the linear conductance per square meter of the MLI stack vs. the average temperature between the two out-facing layers

MLI thermal conductance

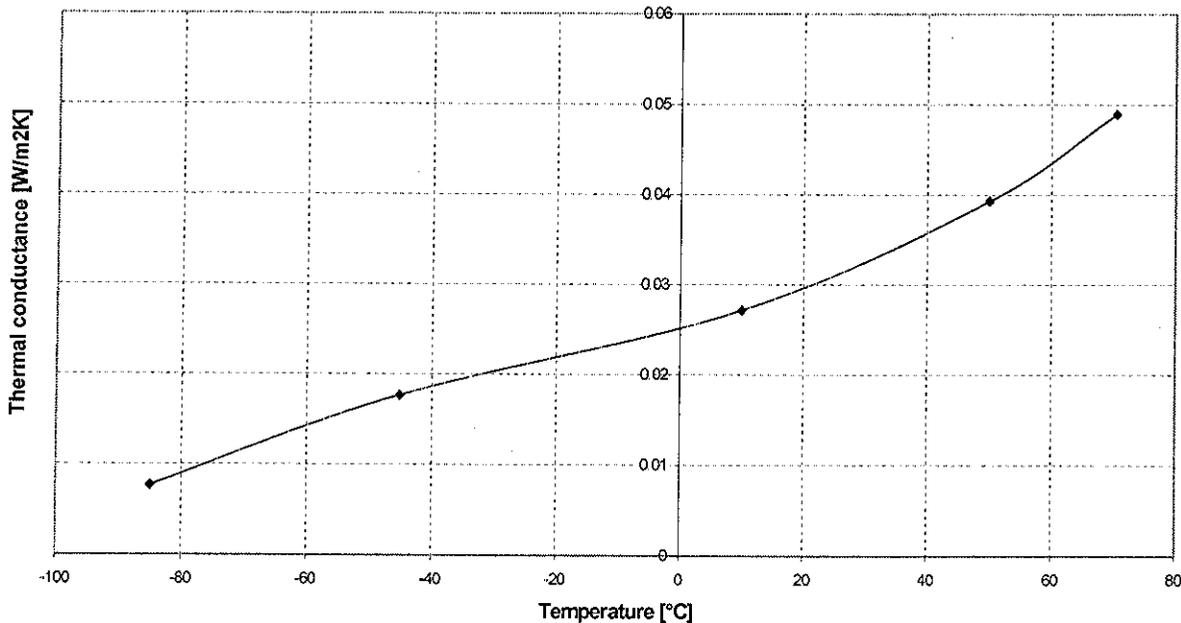


Fig. 5-1 MLI effective thermal conductance

The value obtained from the experimental curve has been then multiplied by a factor of 5, in order to take into account the performance degradation of MLI due to the fixation points and handling.

The external layer of MLI blanket is made of white Beta-cloth and its thermal optical properties both BOL and EOL are listed in the following table:

<i>Beta-cloth</i>	BOL (cold analysis)	EOL (hot analysis)
α	0.2	0.47
ε	0.9	0.86

Tab. 5-1 Beta-Cloth thermal optical properties

6. THERMAL LOADS

6.1 INTERNAL LOADS

Totally 3.68W are dissipated on 76 PMTs (48.4mW each).

The dissipation of the PMT electronics is located on the central board (10.8mW) and on the inner board (37.6mW).

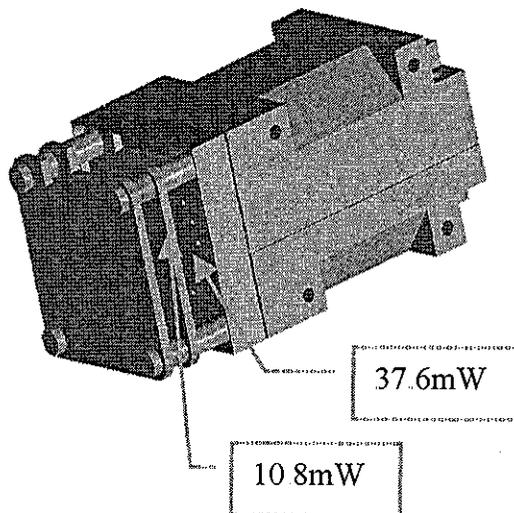


Fig. 6-1 PMT dissipation sharing

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6.2 EXTERNAL LOADS

TOF is located in AMS-02 experiment , which experiences typical external ISS payloads environmental conditions. In particular, ISS orbiting in its Low Earth Orbit experiences typical fluxes of LEO satellites:

- Solar visible radiation
- Albedo (given by the fraction of the Sun energy diffusely reflected by Earth)
- Infrared Earth contribution.

TOF location makes it subjected not only to these direct impinging fluxes, but also to reflections of the aforementioned contributions by other ISS elements.

TOF impinging heating rates, radiative links and sink temperatures have been generated at system level by AMS-02 thermal team.

7. THERMAL MODELLING

7.1 PHYSICAL PROPERTIES

7.1.1 MATERIALS AND MATERIAL PROPERTIES

The following table shows the main TOF materials and the conductivities used in the thermal mathematical model:

Component	Material	Specific Heat [J/kg/K]	Conductivity [W/m/K]
External box	Carbon Fiber	500	200
Brackets	Plexiglass	1297	0.15

Tab. 7-1 Summary of used materials

The dependence from temperature of the above mentioned quantities has been neglected.

7.1.2 CONTACT CONDUCTANCE

The following values have been used to introduce in the model the thermal joint conductance between different parts:

- **1000 W/m²K** : contact conductance between PMTs and Plexiglas bracket
- **300 W/m²K** : contact conductance between Plexiglas bracket and carbon fiber box

obtained as results of experimental test activities.



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7.2 THERMAL MATHEMATICAL MODEL

The main division in thermal submodels (used in SINDA code) is listed in the following table:

SUBMODEL NAME	DESCRIPTION	NUMBER OF NODES
BOX	Central part of the carbon fiber boxes	53
BOX1	RAM side of the carbon fiber box	109
BOX2	WAKE side of the carbon fiber box	109
BOX3	STARBOARD side of the carbon fiber box	61
BOX4	PORT side of the carbon fiber box	61
PMT1	PMTs of BOX1	120
PMT2	PMTs of BOX2	120
PMT3	PMTs of BOX3	126
PMT4	PMTs of BOX4	126
Total number of nodes		885

Tab. 7-2 Submodel lists and number of nodes

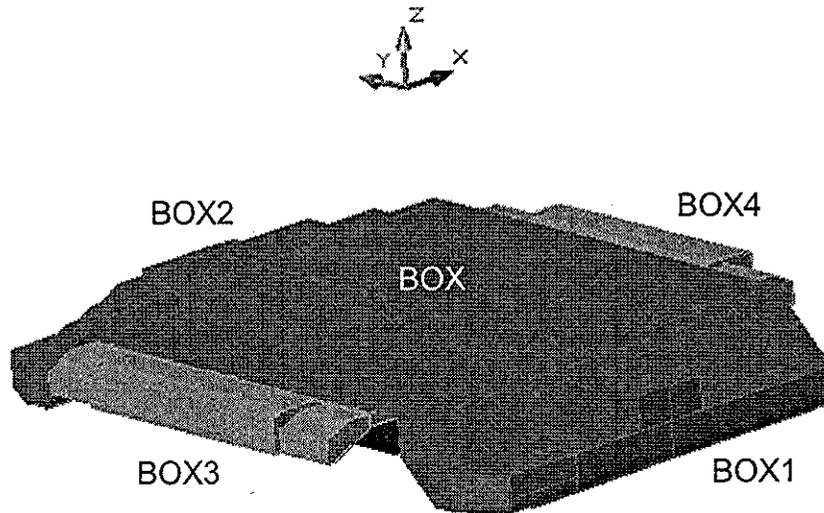


Fig. 7-1 Submodels in AMS-02 coordinate system

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7.2.1 BOX1 AND BOX2 NODAL BREAK-DOWN

Sub-models BOX1 and BOX2 are respectively located on the RAM and WAKE side and they have the same nodal break-down.

The inner part of the carbon fiber box is , from the optical point of view, reflective while the external part is covered with MLI blankets. The external layer of MLI blanket is made of Beta-cloth and its thermal optical properties both BOL and EOL are listed in

Tab. 7-3.

The nodes included in the model are listed in the following table, with their properties:

NODE NUMBER	DESCRIPTION	ϵ BOL	α BOL	ϵ EOL	α EOL
101÷124	Box walls (inner side)	0.05	-	0.05	-
151÷174					
3101÷3124	MLI (outer layer)	0.9	0.22	0.86	0.47
3151÷3174					
1000÷1009	PMT supports	0.05	-	0.05	-

Tab. 7-3 BOX1 and BOX2 nodes numbering

7.2.2 BOX3 AND BOX4 NODAL BREAK-DOWN

Submodels BOX3 and BOX4 are respectively located on the STARBOARD and PORT side and they have the same nodal breakdown.

The inner part of the carbon fiber box is reflective while the external part is covered with MLI blankets. The external layer of MLI blanket is made of white Beta-cloth and its thermal optical properties both BOL and EOL are listed in Tab. 7-4.

The nodes included in the model are listed in the following table, with their properties:

NODE NUMBER	DESCRIPTION	ϵ BOL	α BOL	ϵ EOL	α EOL
101-102	Box walls (inner side)	0.05	-	0.05	-
104÷114					
117-118					
151-152					
154÷164					
167-168	MLI (outer side)	0.9	0.22	0.86	0.47
3101-3102					
3104÷3114					
3117-3118					
3151-3152					
3154÷3164					
3167-3168					

Tab. 7-4 BOX3 and BOX4 nodes numbering

7.2.3 BOX NODAL BREAK-DOWN

This submodel contains the central part of the two different carbon fiber boxes.

The external part of the carbon fiber box is covered with MLI blankets, while the inner part is inactive, since the radiation between the inner box and the scintillator fibers is negligible.

The external layer of MLI blanket is made of white Beta-cloth and its thermal optical properties both BOL and EOL are listed in Tab. 7-5.

The nodes included in the above mentioned model are listed in the following table, with their properties:

NODE NUMBER	DESCRIPTION	ϵ BOL	α BOL	ϵ EOL	α EOL
11÷14 21÷24	Box walls (inner side)	0.05	-	0.05	-
33-43 41-51					
311-312					
333-343 341-351	MLI (outer side)	0.9	0.22	0.86	0.47

Tab. 7-5 BOX nodes numbering

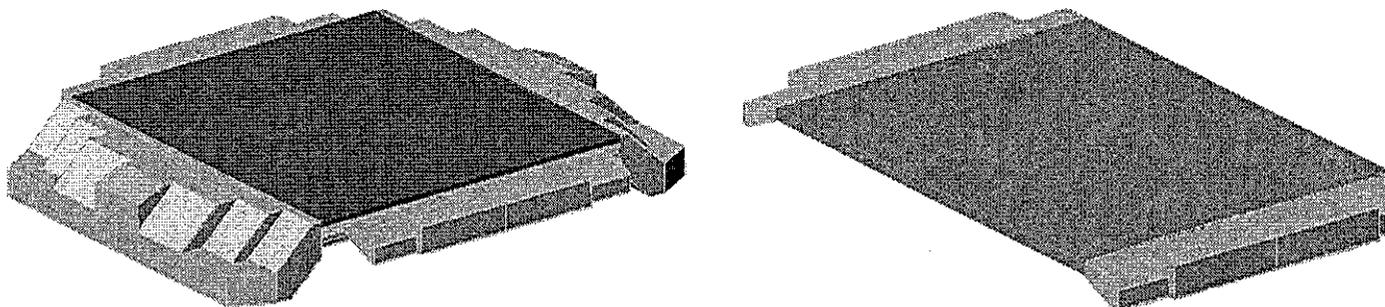


Fig. 7-2 BOX submodel

7.2.4 PMTS

7.2.4.1 PMT1 AND PMT2 NODAL BREAK-DOWN

Twenty different PMT assemblies are included in PMT1 and PMT2 submodels. They're the PMTs included in the RAM and WAKE side of the carbon fiber box, BOX1 and BOX2 respectively. The following image shows the PMTs disposition inside the BOX1:

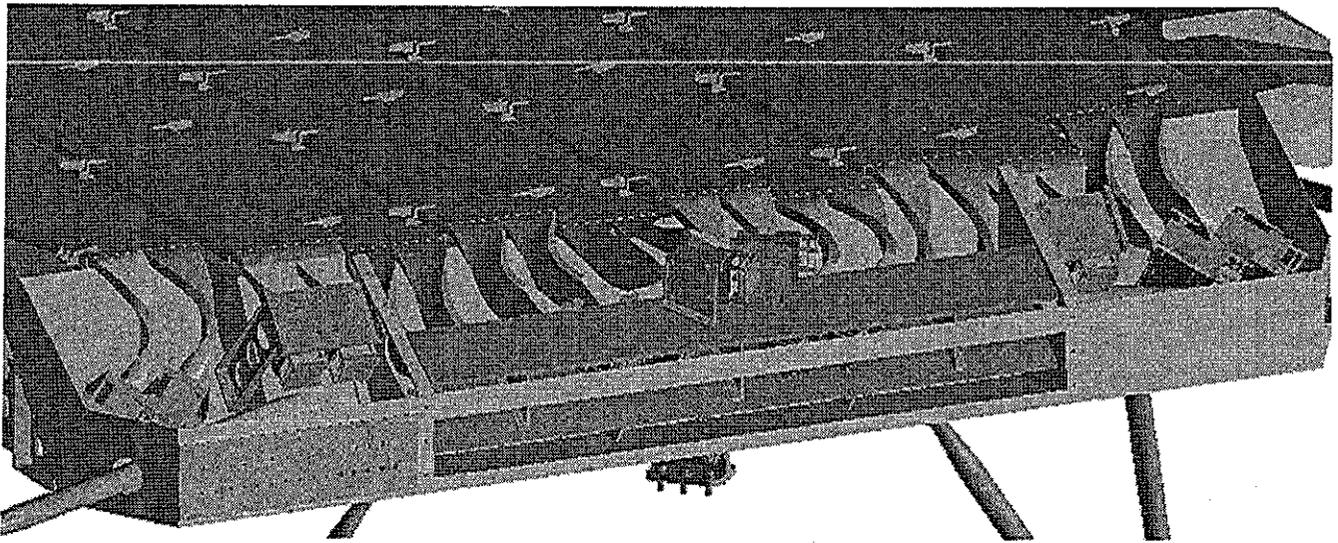


Fig. 7-3 PMTs in RAM direction. WAKE disposition is symmetric

For each PMT package the following nodal break-down has been implemented and the node numbering is listed in the following table:

PMTs nodes included in the model are listed in the following table, with their properties (see also Fig. 7-4):

NODE NUMBER	DESCRIPTION	MATERIAL	ϵ BOL	ϵ EOL	THERMAL CAPACITANCE [J/°C]	DISSIPATION [W]
x1	PMT case	polycarbonate	0.85	0.85	98.4	-
x2	Central electronic board	Cu+FR4	0.7	0.7	2.22	0.0108
x3	Outer electronic board					-
x4	Inner electronic board					0.0376
x5	PMT	-	-	-	arithmetic	-
x9	Bracket	Plexiglass	-	-	43.8	-

Tab. 7-6 PMTs nodes numbering

The first digit in node's ID number (x in the table) indicates PMT's number (x=1, 2, ..., 20)



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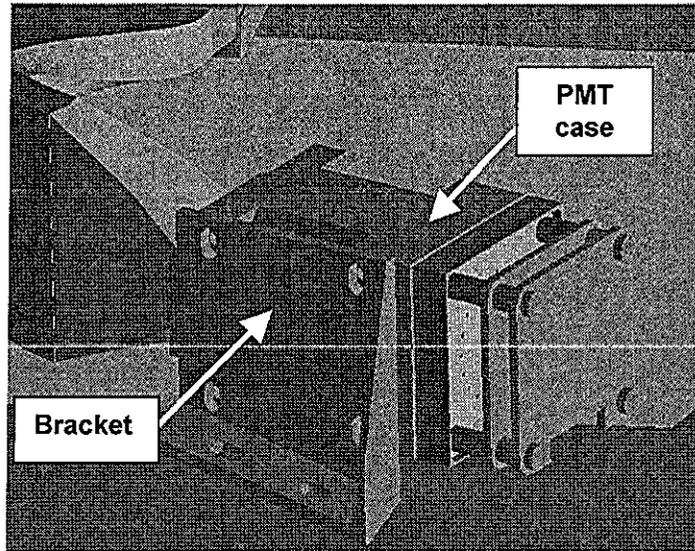


Fig. 7-4 PMT and bracket in RAM and WAKE direction

7.2.4.2 PMT3 AND PMT4 NODAL BREAK-DOWN

Eighteen different PMT assemblies are included in PMT3 and PMT4 submodels. They're the PMT's included in the STARBOARD and PORT side of the carbon fiber box, BOX3 and BOX4 respectively. The following image shows the PMT's disposition inside the BOX3:

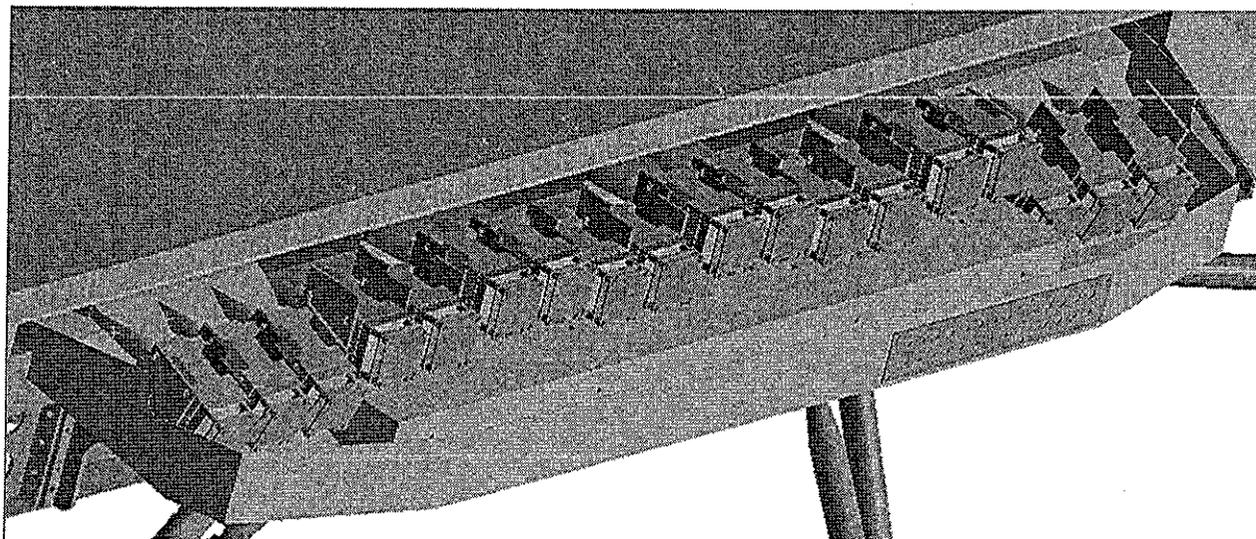


Fig. 7-5 PMT's in STARBOARD direction. PORT disposition is symmetric

For each PMT package the following nodal break-down has been implemented and the node numbering is listed in the following table (see also Fig. 7-6):

NODE NUMBER	DESCRIPTION	MATERIAL	ϵ BOL	ϵ EOL	THERMAL CAPACITANCE [J/°C]	DISSIPATION [W]
x1	PMT case	polycarbonate	0.85	0.85	98.4	-
x2	Central electronic board	Cu+FR4	0.7	0.7	2.22	0.0108
x3	Outer electronic board					-
x4	Inner electronic board					0.0376
x5	PMT	-	-	-	arithmetic	-
X8	Bracket	Plexiglass	-	-	10.3	-
x9	Bracket					-

Tab. 7-7 PMT's nodes numbering

The first digit in node's ID number (x in the table) indicates PMT's number (x=1, 2, ..., 18)



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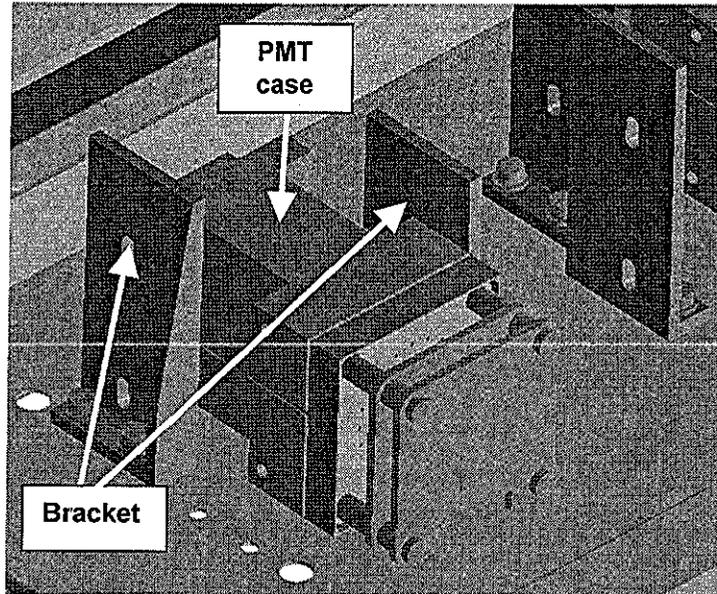


Fig. 7-6 PMT and brackets in STARBOARD and PORT direction



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7.3 GEOMETRIC MATHEMATICAL MODEL

A geometric mathematical model has been developed to calculate the inner radiative coupling among the different surfaces of the box, the PMTs and the brackets and to calculate the outer coupling among the MLI and the external environment.

The RADKS number has been limited choosing a cutoff fraction of 0.001: all the radiative links with a view factor lower than this amount have been neglected.

The following images show the geometric models of the relevant different parts:

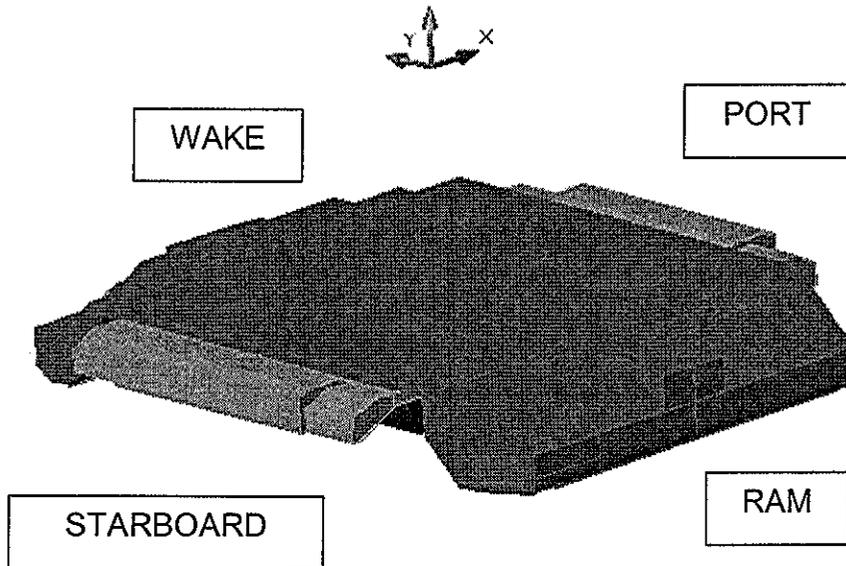


Fig. 7-7 View of the geometrical model of ToF

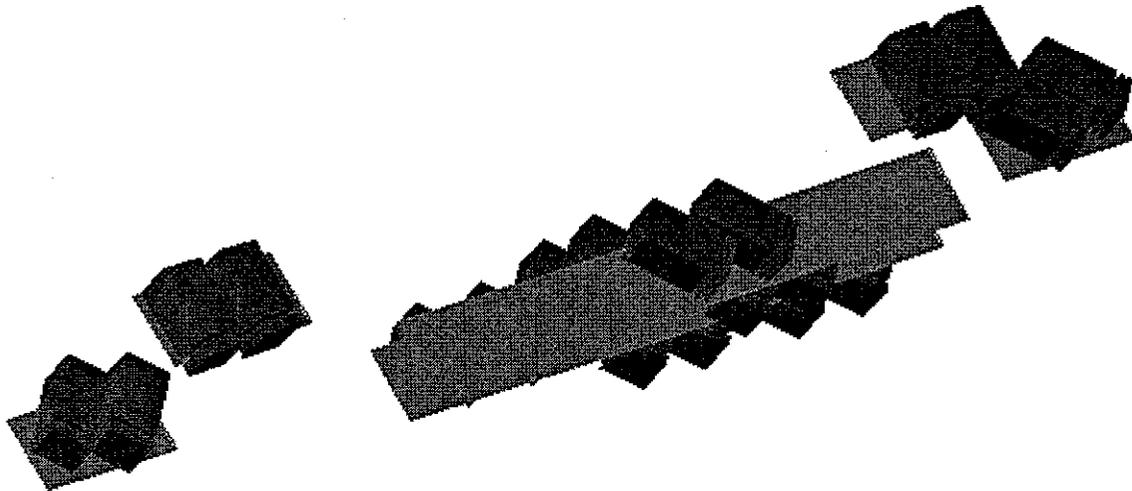


Fig. 7-8 View of the geometrical model of the PMTs and their supports in BOX1(RAM). WAKE disposition is symmetric



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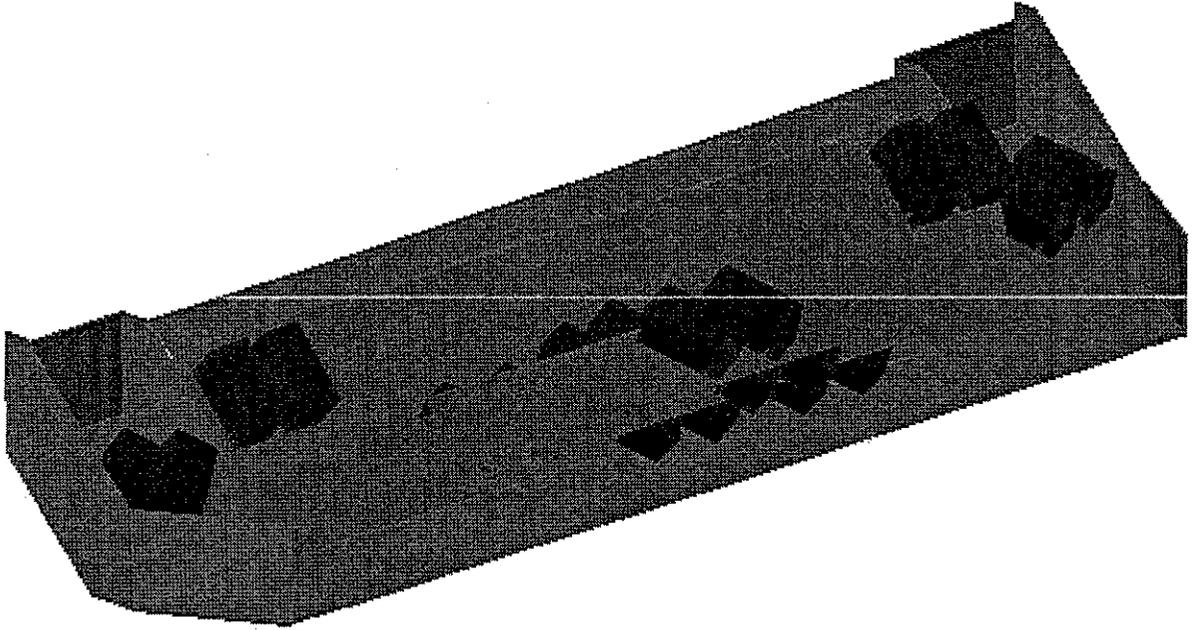


Fig. 7-9 View of the geometrical model of the PMTs and supports in BOX1(RAM). WAKE disposition is symmetric.

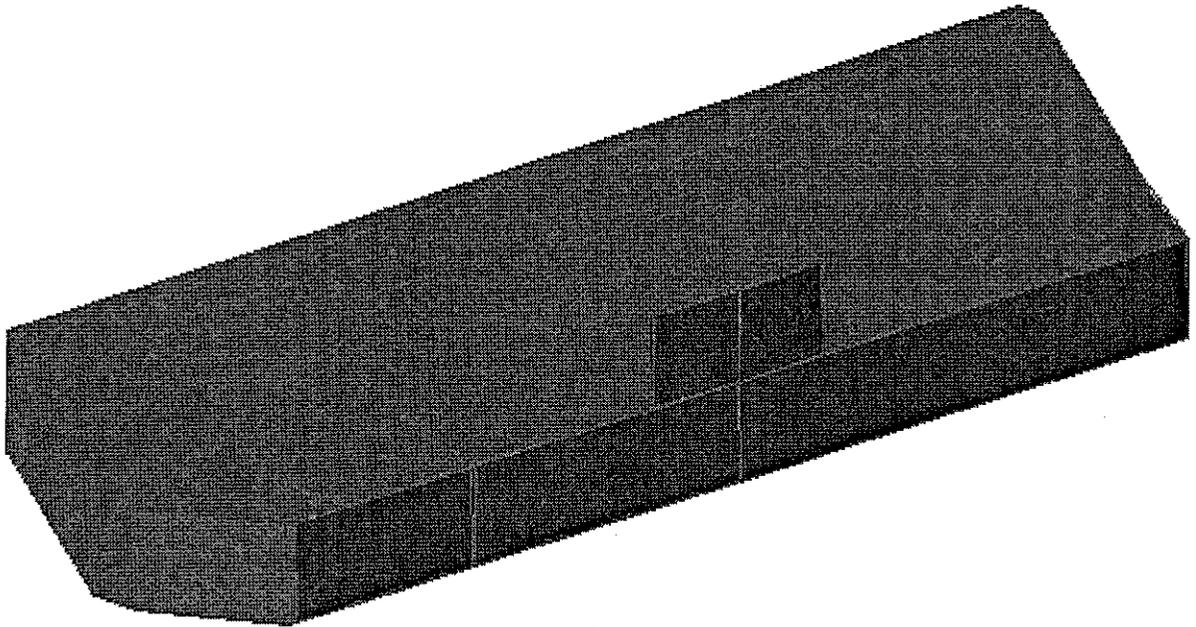


Fig. 7-10 View of the geometrical model of BOX(RAM). WAKE is symmetric



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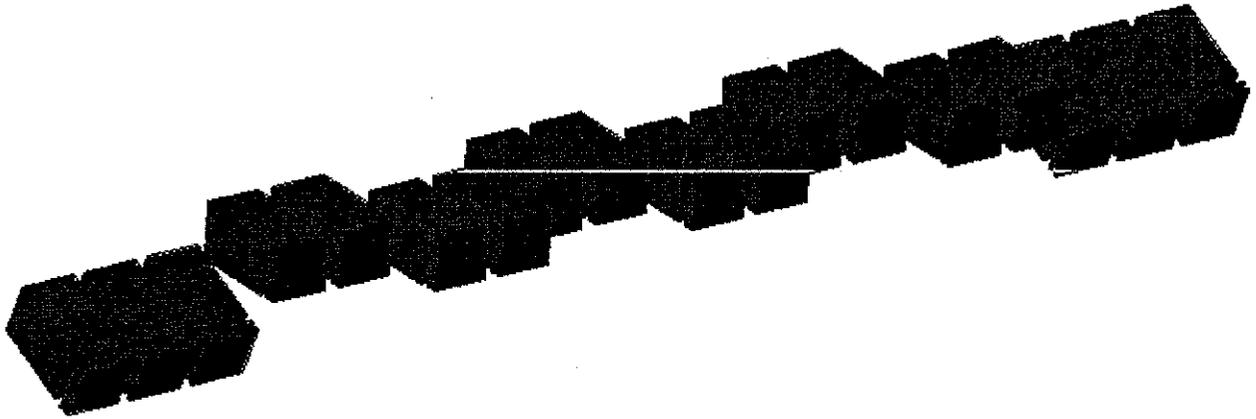


Fig. 7-11 View of the geometrical model of the PMTs in BOX3 (STARBOARD). PORT disposition is symmetric.

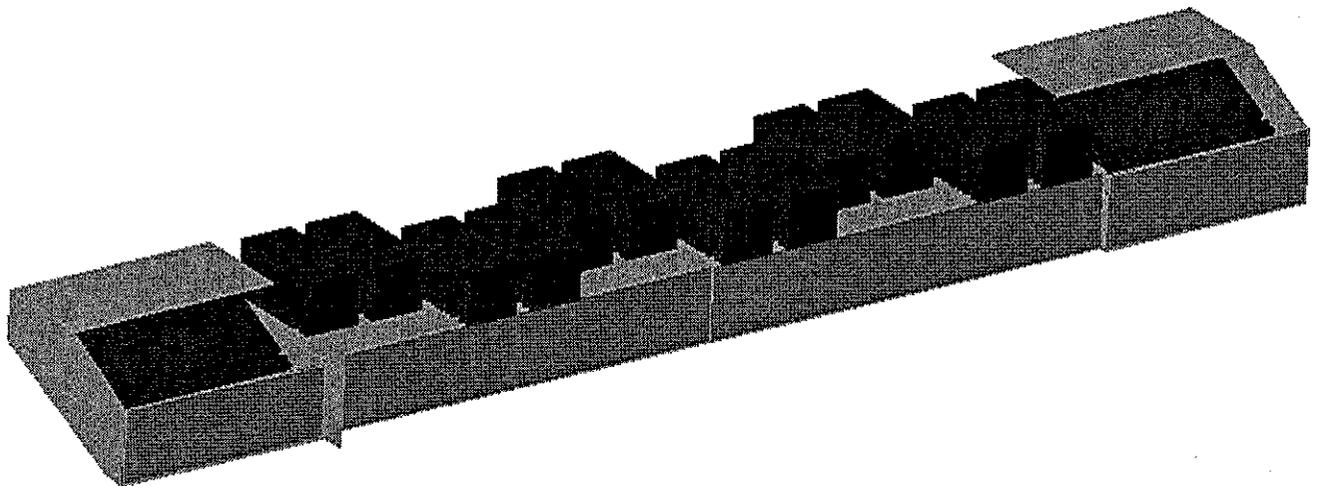


Fig. 7-12 View of the geometrical model of BOX3 (STARBOARD). PORT disposition is symmetric.



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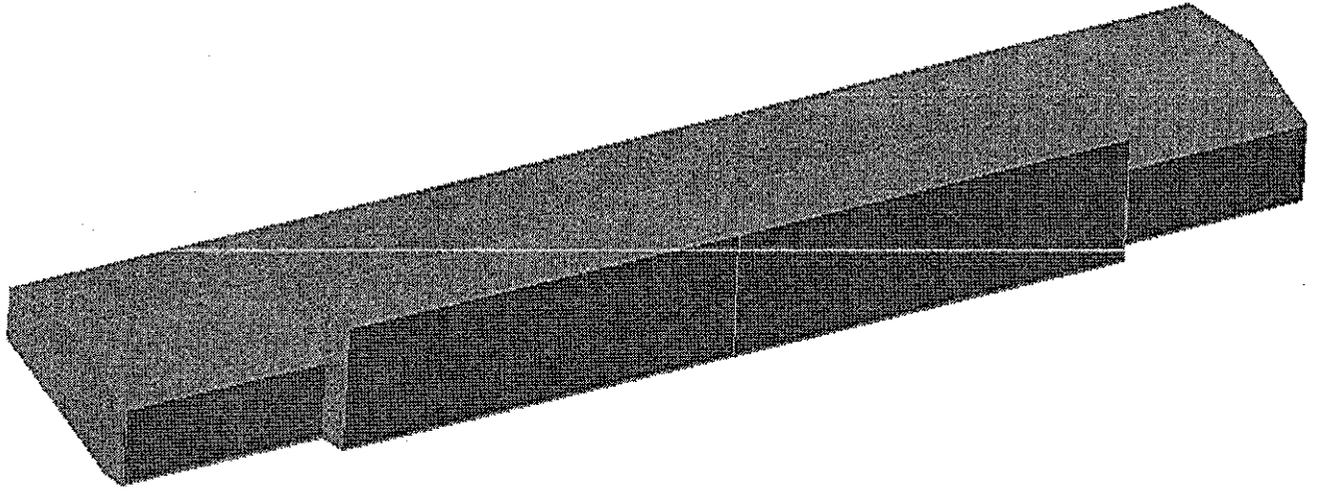


Fig. 7-13 View of the geometrical model of BOX3 (STARBOARD). PORT is symmetric.

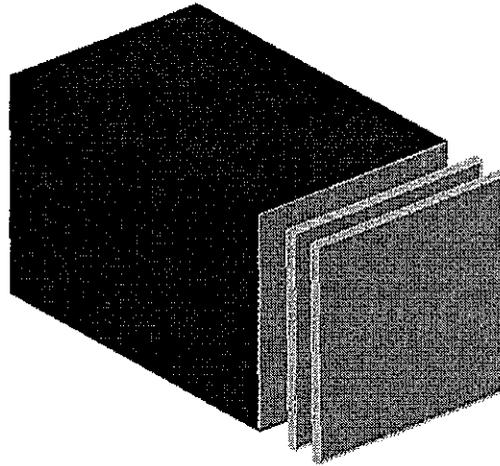


Fig. 7-14 View of the geometrical model of a PMT.

8. ANALYSIS RESULTS

In the following sections the results of the thermal analysis are presented for hot and cold design cases.

The analysis has been performed using I/F thermal data, hot and cold, properly selected by AMS-02 thermal team at system level

I/F thermal data are constituted of :

- Sink temperatures for each of the external facing surfaces
- Impinging heat fluxes (absorbed) for each of the external facing surfaces
- Radiative links between each of the external facing surfaces and sink nodes
- Conductive I/F temperatures for mechanical interfaces

I/F data set are mainly related to the Minimum Propulsion Attitude (MPA) of the International Space Station, characterized by a yaw angle of -2° , a pitch angle of -10° and a roll angle of $+1^\circ$. This attitude minimizes, when the Space Shuttle is docked to the ISS, the propellant needed to maintain the orbit, vs. the drag forces of the residual atmosphere.

Worst cold and hot thermal interfaces, related to less probable but possible ISS attitude, have been generated by the system as well.

All these I/F data have been used for detailed TOF thermal analysis.

The PMTs temperatures results are shown in Tab 8-2 in the following way:

$$\bar{x} \pm \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2}$$

where \bar{x} is the maximum temperature results of the PMTs in each box during the orbit and N is the number of temperature point considered.

The coordinate system used in the table is the following one:

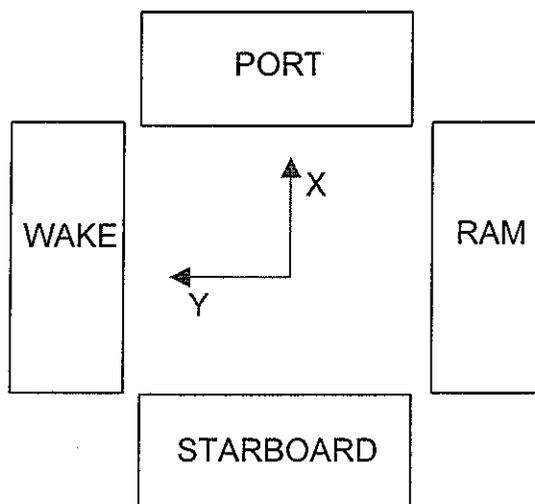


Fig. 8-1 Coordinate system for the presentation of the analysis results

8.1 HOT CASES

A thermal analysis has been performed in the hot conditions to verify that during the hot operative/non operative phases the temperatures of ToF PMTs are kept below their maximum design operative/non operative limits (namely +50°C).

Beta angle	Yaw angle	Pitch angle	Roll angle	Power
-75	-2	-10	+1	ON OFF
-70	-2	-10	+1	ON OFF
-60	-2	-10	+1	ON OFF
-50	-2	-10	+1	ON
0	-2	-10	+1	ON
50	-2	-10	+1	ON
60	-2	-10	+1	ON
70	-2	-10	+1	ON
75	-2	-10	+1	ON
-75	-15	+15	-15	ON OFF

Tab. 8-1 Orbit parameters for hot cases

The last orbit in Tab. 8-1 has an attitude different from the MPA one; it was selected as a worst hot case from AMS-02 thermal team at system level.

The last column shows the AMS-02 subdetectors power condition:

→ ON: all AMS-02 subdetectors are ON

→ OFF: all AMS-02 subdetectors are ON but for TOF, RICH, ECAL, R-crate, E-crate, REPD.

The following table shows the obtained results for the critical orbits

Beta-75 MPA ON	<div style="border: 1px solid black; padding: 5px; width: fit-content; margin: 0 auto;"> $60.2^{\circ}\text{C} \pm 0.3^{\circ}\text{C}$ </div> <div style="border: 1px solid black; padding: 5px; width: fit-content; margin: 10px auto;"> $57.5^{\circ}\text{C} \pm 0.4^{\circ}\text{C}$ </div> <div style="border: 1px solid black; padding: 5px; width: fit-content; margin: 10px auto;"> $57.6^{\circ}\text{C} \pm 0.4^{\circ}\text{C}$ </div> <div style="border: 1px solid black; padding: 5px; width: fit-content; margin: 10px auto;"> $60.6^{\circ}\text{C} \pm 0.3^{\circ}\text{C}$ </div>
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Beta-75 MPA OFF	<p>50.9°C ±0.2°C</p> <p>50.1°C ±0.1°C</p> <p>50.8°C ±0.2°C</p> <p>51.4°C ±0.1°C</p>
Beta-70 MPA ON	<p>49.2°C ±0.4°C</p> <p>52.2°C ±0.3°C</p> <p>49.6°C ±0.4°C</p> <p>52.4°C ±0.4°C</p>
Beta-70 MPA OFF	<p>42.2°C ±0.1°C</p> <p>41.4°C ±0.1°C</p> <p>42.2°C ±0.2°C</p> <p>42.6°C ±0.1°C</p>



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Beta-60 MPA ON	$41.0^{\circ}\text{C} \pm 0.4^{\circ}\text{C}$ $37.5^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ $38.0^{\circ}\text{C} \pm 0.4^{\circ}\text{C}$ $40.9^{\circ}\text{C} \pm 0.4^{\circ}\text{C}$
Beta-75-15+15-15 ON	$61.9^{\circ}\text{C} \pm 0.3^{\circ}\text{C}$ $59.4^{\circ}\text{C} \pm 0.4^{\circ}\text{C}$ $59.2^{\circ}\text{C} \pm 0.3^{\circ}\text{C}$ $62.2^{\circ}\text{C} \pm 0.3^{\circ}\text{C}$
Beta-75-15+15-15 OFF	$51.8^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$ $52.9^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$ $52.3^{\circ}\text{C} \pm 0.2^{\circ}\text{C}$ $53.1^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$

Tab. 8-2 Temperature predictions for PMTs in hot operative/non operative cases

8.2 COLD CASES

A thermal analysis has been performed in the cold conditions to verify that during the cold operative/non operative phases the temperatures of ToF PMTs are kept above their minimum design operative/non operative limits (namely -30°C).

Beta angle	Yaw angle	Pitch angle	Roll angle	Power
0	-2	-10	+1	ON OFF
0	0	0	-15	ON OFF

Tab. 8-3 Orbit parameters for cold cases

For the cold cases the analysis has been limited to the coldest case between the MPA orbits and to an extreme cold orbit selected by AMS-02 thermal team at system level.

The last column shows the AMS-02 subdetectors power condition:

- ON: all AMS-02 subdetectors are ON
- OFF: all AMS-02 subdetectors are OFF but the heaters that guarantee the minimum non operative temperatures for the AMS-02 system.

The following table shows the obtained results using the coordinate system shown in Fig. 8-1.



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Beta_0_0_0-15 ON	<p>Diagram showing four temperature points for the Beta_0_0_0-15 ON state:</p> <ul style="list-style-type: none">Top: $-7.1^{\circ}\text{C} \pm 0.6^{\circ}\text{C}$Left: $-13.3^{\circ}\text{C} \pm 0.8^{\circ}\text{C}$Right: $-12.5^{\circ}\text{C} \pm 0.8^{\circ}\text{C}$Bottom: $-8.1^{\circ}\text{C} \pm 0.7^{\circ}\text{C}$
Beta_0_0_0-15 OFF	<p>Diagram showing four temperature points for the Beta_0_0_0-15 OFF state:</p> <ul style="list-style-type: none">Top: $-25.6^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$Left: $-25.6^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$Right: $-25.6^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$Bottom: $-25.7^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$
Beta_0_MPA ON	<p>Diagram showing four temperature points for the Beta_0_MPA ON state:</p> <ul style="list-style-type: none">Top: $-4.2^{\circ}\text{C} \pm 0.6^{\circ}\text{C}$Left: $-10.2^{\circ}\text{C} \pm 0.8^{\circ}\text{C}$Right: $-9.5^{\circ}\text{C} \pm 0.8^{\circ}\text{C}$Bottom: $-5.2^{\circ}\text{C} \pm 0.7^{\circ}\text{C}$

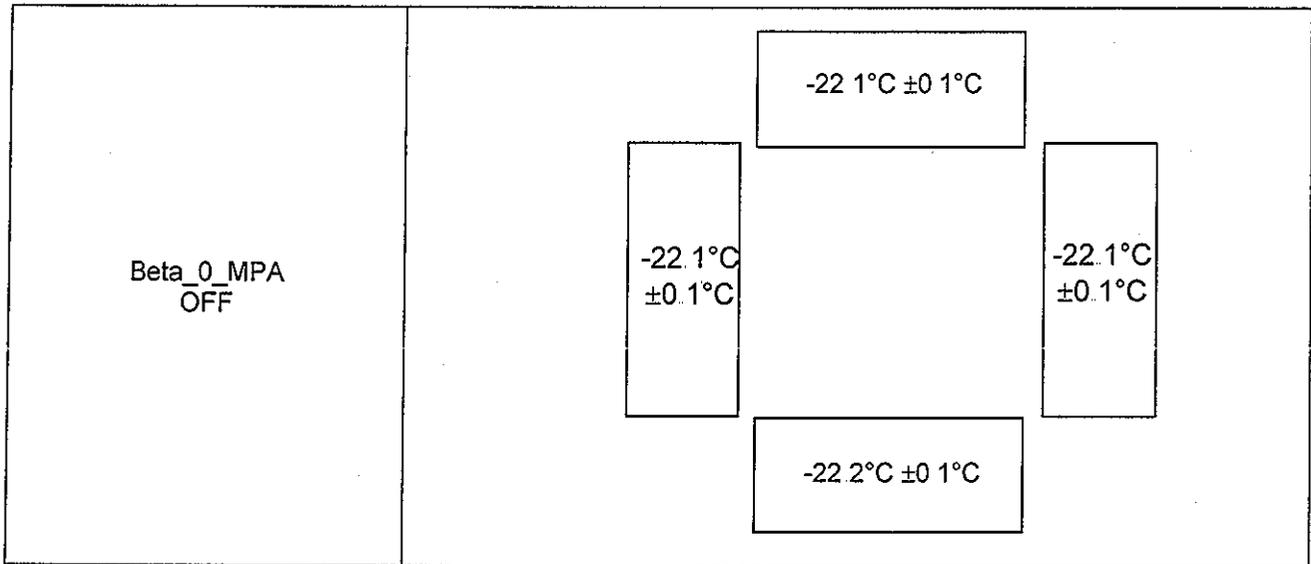


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Tab. 8-4 Temperature predictions for PMTs in cold operative/non operative cases

9. CONCLUSIONS

The Thermal Mathematical and Geometric models of ToF have been described. Analysis results have been presented and they can be summarized as follows:

□ *Operative/non operative Hot cases*

The performed runs show that positive margins exist for the operative cases but for the orbits

- B-75 MPA
- B-75-15-20-15
- B-70 MPA

In these cases the PMTs temperature is out of the maximum acceptable temperature (namely +50°C) as shown in the next table (+5°C of temperature uncertainty has been considered) :

	PMT maximum temperature prediction , °C	PMT maximum predicted Uncertainty , °C	PMT temperature requirement, °C	Margin, °C
B-75 MPA	+60.6	+65.6	+50	-15.6
B-75-15-20-15	+62.2	+67.2	+50	-17.2
B-70 MPA	+52.4	+57.4	+50	-7.4
B-60 MPA	+41.0	+46.0	+50	+4.0

Tab. 9-1 Hot operative cases PMT temperature predictions and resulting margins

Due to the negative margins occurring in the beta angle range $\beta -70^\circ$ e $\beta -75^\circ$, independently on the attitude of the ISS, the TOF can not operate respecting the requirement.

Since the ISS stays only 5.6 days per year between $\beta -70^\circ$ e $\beta -75^\circ$, resulting in 1.5% of the entire mission duration, a possible recovery action is to switch off the ToF subsystem during these few days, without compromising the mission scientific goal.

The following table shows temperature predictions for the cases presented in Tab. 9-2 but considering non operative conditions:

	PMT maximum temperature prediction , °C	PMT maximum predicted Uncertainty , °C	PMT temperature requirement, °C	Margin, °C
B-75 MPA	+51.4	+56.4	+50	-6.4
B-75-15-20-15	+53.1	+58.1	+50	-8.1
B-70 MPA	+42.6	+47.6	+50	+2.4

Tab. 9-2 Hot non operative cases PMT temperature predictions and resulting margins

The non operative runs show that the non operative PMT requirements are still not fulfilled for $\beta -75^\circ$ (both MPA and worst hot attitude).

In order to face this issue a functional PMT test for a non operative extended range is foreseen. The same philosophy has been applied to RICH detector.

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A functional / electrical test is in progress to demonstrate the ability of the PMT equipment to work conforming to specification requirements after having experienced the non operative temperature of +60°C for a few days.

□ *Operative/non operative Cold cases*

The performed cold runs show that positive margins exist for the investigated operative/non operative cases:

	PMT minimum temperature prediction , °C	PMT minimum predicted + Uncertainty , °C	PMT temperature requirement, °C	Margin, °C
B 0 0 0 -15	-13.3	-18.3	-30	+11.7
B 0 MPA	-10.2	-15.2	-30	+14.8

Tab. 9-3 Cold operative cases PMT temperature predictions and resulting margins

	PMT minimum temperature prediction , °C	PMT minimum predicted + Uncertainty , °C	PMT temperature requirement, °C	Margin, °C
B 0 0 0 -15	-25.6	-30.6	-30	-0.6
B 0 MPA	-22.1	-27.1	-30	+2.9

Tab. 9-4 Cold non operative cases PMT temperature predictions and resulting margins

No need for heaters is envisaged.